

VERITAS Observations of the BL Lac Object PG 1553+113 Between May 2010 and May 2011

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Abstract: VERITAS, an array of imaging atmospheric-Cherenkov telescopes, studies blazars in the energy range between 100 GeV and 30 TeV. With its excellent sensitivity at these energies, and ever-deepening source exposures, VERITAS is in a position to probe distant blazars for clear absorption signatures in their very-high-energy gamma-ray spectra due to interactions with the extragalactic background light (EBL). We discuss results from recent VERITAS observations of PG 1553+113 ($z > 0.4$) which have resulted in the most significant very-high-energy detection ever obtained for this source. The most recent VERITAS spectral measurements are used to place an upper limit on the source redshift of $z < 0.5$ at the 95% confidence level. Also discussed are the prospects of using these observations, along with those of other hard-spectrum blazars, to place constraints on the EBL.

Keywords: blazars, extragalactic background light, gamma rays, PG 1553+113, VERITAS

1 Introduction

PG 1553+113 is a high-frequency peaked BL Lac object (HBL) [1, 2, 3] discovered by Green et al. (1986) [4]. Evidence of very-high-energy (VHE) gamma-ray emission from this source was first detected by HESS in 2005 [5]. This was later confirmed by observations made with the MAGIC telescope in 2005 and 2006 [6]. Due to its featureless spectrum, the redshift of PG 1553+113 remains uncertain. However, constraints on the redshift have been continually narrowing with improved optical measurements and limits from VHE observations (e.g., [7, 8, 5, 9]).

Recent measurements using the *Hubble Space Telescope/Cosmic Origins Spectrograph* place a lower limit on the redshift of PG 1553+113 of $z > 0.4$ [10]. Statistical arguments are also presented placing a 1σ upper limit of $z \leq 0.58$.

These limits suggest that PG 1553+113 is one of the most distant sources ever detected at VHE, and perhaps the most distant source of all. This makes it an incredibly interesting source for studying the extragalactic background light (EBL). As VHE gamma rays traverse the distance between their point of origin and the Earth, they can interact with the diffuse infrared radiation field known as the EBL [11, 12]. The optical/infrared EBL consists of the progressive emission of galaxies and active galactic nuclei (AGN), and the absorption and re-radiation of this emission by dust (see [13, 14] for a review). The level of gamma-ray absorption due to the EBL increases with both gamma-ray energy and source distance. Consequently, observed VHE spectra are

increasingly softened, with respect to their intrinsic emission, as the source becomes more distant. This effectively produces a gamma-ray horizon, beyond which gamma rays of a particular energy are fully absorbed.

2 Observations

Very-high-energy observations of distant blazars are a valuable tool for constraining the EBL. As such, PG 1553+113 has been an important component in the long-term blazar science program of the Very Energetic Radiation Imaging Telescope Array System (VERITAS) collaboration.

The VERITAS observatory is an array of four 12-meter imaging atmospheric-Cherenkov telescopes (IACTs) located at the Fred Lawrence Whipple Observatory (FLWO) in southern Arizona [15]. Each reflector comprises 350 hexagonal mirrors following the Davies-Cotton design. The focal plane camera consists of 499 photomultiplier tubes covering a 3.5° field of view. Its large collection area ($\sim 10^5 \text{ m}^2$), in conjunction with the stereoscopic imaging of air showers, allows VERITAS to detect very-high-energy gamma rays between energies of 100 GeV and 30 TeV with an energy resolution of $\sim 15\text{--}25\%$ and an angular resolution of $\sim 0.1^\circ$. A source with a flux 1% that of the Crab Nebula can be detected by VERITAS in ~ 25 hours with a statistical significance of 5 standard deviations (σ).

PG 1553+113 was observed by VERITAS between May 2010 and May 2011 for a total of nearly 72 hours. Excluding bad-weather runs, and some 3-telescope data not yet

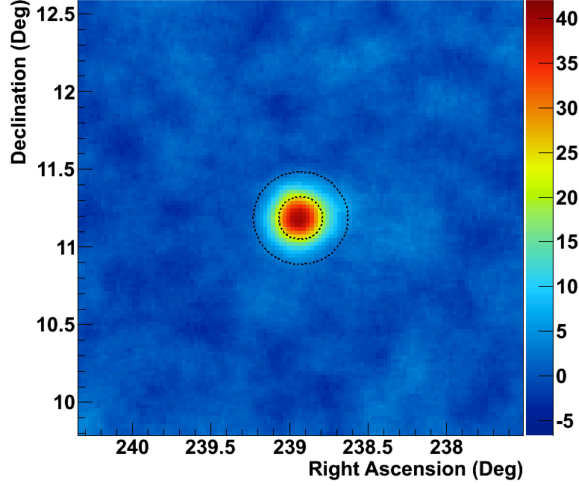


Figure 1: Significance map of PG 1553+113. The inner dashed circle outlines the ON region used in the analysis (see Section 3). The outer dashed circle indicates the region excluded from the background estimation.

analyzed, the dataset presented here consists of 50 hours of live time. All observations were performed in *wobble* mode, with the source offset from the center of the field of view by 0.5° . This allows for simultaneous background estimation and source observation. Four wobble directions are used (North, South, East, West) and are alternated from run to run.

3 Analysis

The standard VERITAS analysis chain begins with the calibration of camera gains using nightly flasher runs. Each camera image is then cleaned, with cuts being placed on each pixel according to its signal-to-noise ratio for a given event. The cleaned images are then characterized, using the standard Hillas parameters [16], by calculating the moments of the light distributions. Cuts on these image parameters are placed to maximize the rejection of the cosmic-ray background while minimizing the loss of gamma rays. Images from a given event passing the requisite cuts are then combined stereoscopically to reconstruct the direction of the incident gamma ray in the camera plane and the core location of the air shower in the ground plane. The energies of reconstructed events are estimated using Monte Carlo simulations. Separate simulations are used for data taken during the summer (May-October) and winter (November-April) months, with each set of simulations using atmospheric models appropriate for that time of year. For the analysis of PG 1553+113, a circular region of radius 0.14° , centered around the source direction, was used to calculate the number of ON counts in the data. The OFF counts were determined using the reflected-regions background model [17] with 7 background regions. The detection significance was calculated following Equation 17 of [18].

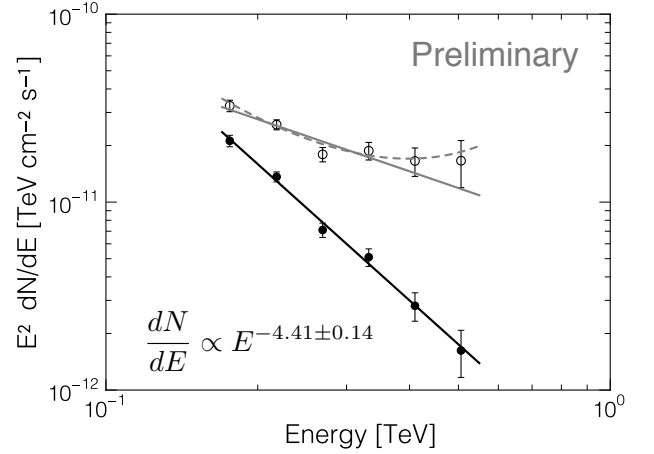


Figure 2: Observed spectrum of PG 1553+113 (solid black points and line). The intrinsic spectrum was calculated assuming a redshift of $z = 0.5$ and the low star formation rate EBL model of [22] is given by the open data points (see Section 5). A simple power-law fit, and power-law fit with an exponential rise, are shown by the grey solid and dashed curves, respectively. The flux on the y-axis is multiplied by E^2 , where E is the energy in TeV.

4 Results

The VERITAS observations of PG 1553+113 between May 2010 and May 2011 resulted in a detection significance of 39σ , the most significant VHE detection ever obtained for this source. The significance map of these observations is shown in Figure 1. The time-averaged energy spectrum for the full observation period is shown in Figure 2. The spectrum spans energies from 175 GeV to 500 GeV, with all flux points having a significance greater than 3σ . A power-law fit to the spectrum yields

$$\frac{dN}{dE} = (6.66 \pm 0.34) \times 10^{-11} \left(\frac{E}{0.3 \text{ TeV}} \right)^{-4.41 \pm 0.14} \text{ cm}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}, \quad (1)$$

with a χ^2/ν of 2.603/4, corresponding to a fit probability of 63%. The time-averaged integral flux above 200 GeV is

$$\Phi(> 200 \text{ GeV}) = (2.34 \pm 0.12) \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}, \quad (2)$$

where the best-fit value for the spectral index has been assumed. This corresponds to $\sim 10\%$ of the Crab Nebula flux. The errors in Equations 1 and 2, and all errors given below, are statistical errors only. Table 1 provides a summary of the observations and results. The temporal analysis for the lightcurve of PG 1553+113 is currently under way.

5 Constraining the Redshift of PG 1553+113

As previously mentioned, the redshift of PG 1553+113 is uncertain, with a firm lower limit of $z > 0.4$ placed by [10].

Table 1: Summary of VERITAS observations from 2010 and 2011.

| | Live Time [hours] | Significance [σ] | Γ ($dN/dE \propto E^{-\Gamma}$) | $\Phi(> 200 \text{ GeV})$ [$10^{-11} \text{ cm}^{-2} \text{ s}^{-1}$] | % Crab Nebula Flux |
|------|----------------------|------------------------------|---|--|-----------------------|
| 2010 | 27 | 29 | 4.50 ± 0.21 | 2.43 ± 0.14 | 10 |
| 2011 | 23 | 26 | 4.23 ± 0.20 | 2.20 ± 0.16 | 9 |

An upper limit on the redshift can be obtained using the observed VHE spectrum and correcting for attenuation due to the EBL. There are two basic approaches to this technique. The first is simply to calculate the de-absorbed spectrum and place a cut on the hardest (minimum) “acceptable” value for the intrinsic VHE spectral index, thereby constraining the maximum redshift. This value can be motivated by theoretical arguments (e.g., [19]) or from observations of the source at lower energies where EBL attenuation is negligible (e.g., [20]). The second approach is to calculate the de-absorbed spectrum and exclude redshifts which produce unphysical features (based on standard blazar emission models), such as an exponential rise, in the spectrum (e.g., [21]).

With the second approach, one must have a way of determining if, for example, an apparent exponential rise is statistically significant. This can be done using the likelihood-ratio test (see, e.g., [18]). Assuming a power-law fit to the intrinsic spectrum is the *null hypothesis*, and a power law with an exponential rise (hereafter exponential power law) is the second hypothesis, the likelihood ratio can be formed as $\lambda = -2 \ln(\mathcal{L}_{\text{null}}/\mathcal{L}_{\text{exp}})$, where $\mathcal{L}_{\text{null}}$ is the likelihood of the power-law fit and \mathcal{L}_{exp} is the likelihood of the exponential power-law fit. The likelihood ratio λ will be distributed like χ^2 with $\nu_{\text{null}} - \nu_{\text{exp}} = 1$ degree of freedom. The null hypothesis (power-law fit) can then be excluded, and the second hypothesis (exponential power-law fit) therefore accepted, at some confidence level (C.L.) based on the value of the likelihood ratio.

An EBL spectral energy distribution (SED) must be assumed in order for the intrinsic source spectrum to be calculated. To obtain a true upper limit on the redshift, an SED corresponding to the lowest allowed level of EBL should be chosen, hence yielding the minimum loss of VHE gamma rays due to EBL absorption. This will result in softer calculated intrinsic spectra and weaker absorption features, thereby allowing for larger source redshifts.

Both of the aforementioned techniques were applied to PG 1553+133 by [9] using combined MAGIC and HESS spectra. The authors derived 95% C.L. upper limits of $z < 0.69$ and $z < 0.42$ using the first and second approaches, respectively, and the so-called low-star-formation-rate (Low-SFR) EBL model of [22]. In this work we follow the second approach. Using the spectrum obtained from the 2010-2011 VERITAS observations, and the same EBL SED, we obtain an upper limit on the redshift of PG 1553+113 of $z < 0.5$ at the 95% C.L. We have followed the approach of [23] to account for the effects of EBL evolution. The intrinsic spectrum calculated for a redshift of $z = 0.5$ is shown in

Figure 2, together with the power-law fit and exponential power-law fit.

The redshift upper limit obtained here is in good agreement with the result of [9].¹ The VERITAS result can be improved by expanding the observed spectrum to higher and lower energies, making the analysis more sensitive to features introduced into the intrinsic spectrum at large redshifts for a particular EBL SED.

6 Constraining the EBL Using PG 1553+113 and Other VERITAS Blazars

As the redshift of PG 1553+113 becomes increasingly constrained, it will also become a valuable source for constraining the intensity of the EBL and the shape of its SED. With a known source redshift, the same analysis described in Section 5 can be applied, leaving the redshift fixed and varying the EBL intensity instead. In this case, features in the intrinsic spectrum will result from an increase in EBL intensity rather than an increase in redshift.

As briefly mentioned in Section 5, one approach to constraining the EBL is to use blazar spectra measured at MeV to GeV energies, where EBL attenuation is negligible, as a lower limit to the hardness of the intrinsic TeV spectrum. This method yields reliable results as long as the spectrum does not exhibit an additional TeV spectral component. The *Fermi* Large Area Telescope (LAT), operating in the energy range of ~ 100 MeV to 300 GeV, is ideal for establishing a proxy for intrinsic TeV spectral limits. The degree to which a particular source can constrain the EBL can be quantified using the ratio $\alpha = \Delta\Gamma/D_L$ [20], where $\Delta\Gamma$ is the observed VERITAS spectral index (Γ_{VTS}) minus the LAT measured spectral index (Γ_{LAT}) and D_L is the luminosity distance of the source. A smaller value of α indicates the source will more tightly constrain the EBL.

A number of blazars in the VERITAS catalog are well suited for constraining the EBL, based on their small values of α . These sources are shown in Table 2. It can be seen that all of the sources listed have values of $\alpha < 3 \times 10^{-3} \text{ Mpc}^{-1}$. For comparison, the nearby blazar 1ES 2344+514 has $\alpha = (2.95 - 1.57)/183 \text{ Mpc} = 7.5 \times 10^{-3} \text{ Mpc}^{-1}$, indicating that it is not an ideal source for constraining the EBL using this technique.

1. It is important to note that constraining source redshifts using the EBL is largely dependent on the EBL SED and evolutionary scenario used. Therefore, it is argued here that if two independent analyses, using spectra measured with different instruments, yield redshift upper limits within $\Delta z = 0.08$ of one another, this constitutes good agreement.

Table 2: Blazars in the VERITAS catalog well suited for constraining the EBL. Listed are (left to right) the source name, redshift, luminosity distance, LAT spectral index, VERITAS spectral index, and the difference in spectral indices divided by the luminosity distance. All *Fermi*-LAT spectral indices are taken from the 1FGL catalog (http://fermi.gsfc.nasa.gov/ssc/data/access/lat/1yr_catalog/).

| Source Name | Redshift | D_L [Mpc] | Γ_{LAT} | Γ_{VTS} | $\alpha = \Delta\Gamma/D_L$ [$\times 10^{-3} \text{ Mpc}^{-1}$] |
|---------------|----------|----------------|-----------------------|-------------------------|--|
| RGB J0710+591 | 0.124 | 488 | 1.28 ± 0.21 | 2.69 ± 0.26 | 2.9 |
| 1ES 0229+200 | 0.139 | 542 | - | $2.44 \pm 0.11^\dagger$ | 1.9^\ddagger |
| 1ES 1218+304 | 0.182 | 689 | 1.70 ± 0.08 | 3.07 ± 0.09 | 2.0 |
| RBS 0413 | 0.190 | 716 | 1.47 ± 0.18 | $3.24 \pm 0.84^\dagger$ | 2.5 |
| 1ES 0414+009 | 0.287 | 1017 | 1.94 ± 0.22 | $3.05 \pm 0.41^\dagger$ | 1.2 |
| PG 1553+113 | 0.4–0.5 | 1323–1560 | 1.66 ± 0.03 | 4.41 ± 0.14 | 1.8–2.1 |

[†] Preliminary.

[‡] Assuming $\Gamma_{\text{LAT}} = 1.5$.

By combining the individual limits on the EBL obtained using each source from Table 2, the constraints can be further improved. Many of these sources (PG 1553+113 included) are components of the VERITAS blazar long-term observing plan and will have improved spectral measurement over the years to come. This will continue to tighten the region of parameter space allowed for the intensity and shape of the EBL.

7 Discussion & Conclusions

The VERITAS observations of PG 1553+113 between May 2010 and May 2011 have resulted in the most significant VHE detection of this source to date. A time-averaged observed spectral index of $\Gamma = 4.41 \pm 0.14$ is obtained for the full data set. The time-averaged integral fluxes above 200 GeV for the 2010 and 2011 time periods show no evidence for annual variability. A shorter timescale (\sim daily) variability analysis is currently under way.

We derive an upper limit for the redshift of PG 1553+113 of $z < 0.5$, at the 95% C.L., based on the assumption that the intrinsic spectrum does not rise exponentially with increasing energy above ~ 300 GeV. Combined with the lower limit of [10], this places the redshift in the range $0.4 < z < 0.5$. As the limits on the redshift of PG 1553+113 tighten, this object will become an effective tool for constraining the EBL.

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